Continuous Cropping Systems Reduce Near-Surface Maximum Compaction in No-Till Soils

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Cropping Systems

ABSTRACT

Because of increased concerns over compaction in no-till (NT) soils, it is important to assess how continuous cropping systems influence risks of soil compaction across a range of soils and NT management systems. We quantified differences in maximum bulk density (BD_{max}) and critical water content (CWC) by the Proctor test, field bulk density (ρ_b), and their relationships with soil organic carbon (SOC) concentration across three (>11 yr) cropping systems on a silty clay loam, silt loam, and loam in the central Great Plains. On the silty clay loam, BD_{max} in sorghum [*Sorghum bicolor* (L.) Moench]–fallow (SF) and winter wheat [*Triticum aestivum* (L.)]–fallow (WF) was greater than in continuous wheat (WW) and continuous sorghum (SS) by 0.1 Mg m^{-3} in the 0- to 5-cm soil depth. On the loam, BD_{max} in WF was greater than in W–corn (*Zea mays* L.)–millet (*Panicum liliaceum* L.) (WCM) by 0.24 Mg m^{-3} and perennial grass (GRASS) by 0.11 Mg m^{-3}. On the silt loam, soil properties were unaffected by cropping systems. Elimination of fallowing increased the CWC by 10 to 25%. The ρ_b was greater in WF (1.52 Mg m^{-3}) than in WW (1.16 Mg m^{-3}) in the silty clay loam, while ρ_b under WF and WCF was greater than under WCM and GRASS in the loam for the 0- to 5-cm depth. The BD_{max} and ρ_b decreased whereas CWC increased with an increase in SOC concentration in the 0- to 15-cm depth. Overall, continuous cropping systems in NT reduced near-surface maximum soil compaction primarily by increasing SOC concentration.

Continuous cropping systems under NT are being recognized as an important alternative to crop-fallow systems in the central Great Plains of the United States. Intensified cropping systems have greater benefits than crop-fallow systems (e.g., WF or SF) for conserving soil and water (Peterson and Westfall, 2004), improving soil properties (Shaver et al., 2003; Pikul et al., 2006; Benjamin et al., 2007; Benjamin et al., 2008), and increasing SOC concentration (Bowman et al., 1999; Mikha et al., 2006;) while improving crop production (Anderson et al., 1999; Peterson and Westfall, 2004). Diverse crop rotations and continuous cropping systems return more above- and belowground biomass to soil than cropping systems with extended fallow periods. Annual return of crop residues in NT systems is essential to protect the soil surface from water and wind erosion, reduce water evaporation, increase soil macroaggregation, and enhance C accumulation.

An additional benefit of intensified cropping systems under NT technology may be the reduced susceptibility of soil to compaction. No-till soils are often susceptible to compaction due to lack of disturbance and field equipment traffic. Because of the greater biomass C input than crop-fallow systems, intensified cropping systems often increase SOC concentration over crop-fallow systems (Liebig et al., 2004; Peterson and Westfall, 2004). This increase in SOC may induce resilient properties to soil and provide a buffer against compaction. Influence of increased SOC concentration by continuous cropping systems on soil compactibility requires further research.

The Proctor test is a useful approach to determine soil's susceptibility to compaction (American Society for Testing and Materials, 2007). The Proctor test has been used to determine the BD_{max}, which is equivalent to the maximum compactibility of a soil (Thomas et al., 1996; Aragón et al., 2000; Blanco-Canqui et al., 2009). The Proctor test allows the determination of relative soil bulk density at different soil water contents under standardized compactive forces. The soil water content at which the Proctor bulk density of a soil reaches a maximum value (BD_{max}) is known as the CWC (Krzic et al., 2004; Zhao et al., 2008). The Proctor test has important agronomic uses, but it has not been widely used for assessing differences in soil compactibility among diverse crop rotations managed under NT.

Previous studies have reported that soils under long-term NT systems can be less susceptible to compaction than plowed soils due to NT-induced increase in SOC concentration (Thomas et al., 1996; Blanco-Canqui et al., 2009). Soil resilience or buffering capacity can increase with increasing years following NT adoption as a result of greater accumulation of SOC (Blanco-Canqui et al., 2009). On a silt loam in Kentucky, Thomas et al. (1996) observed

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Abbreviations: BD_{max}, maximum bulk density; CWC, critical water content; NT, no-till; SF, grain sorghum–fallow; SOC, soil organic carbon; SS, continuous sorghum; ρ_b, field bulk density; WCM, wheat–corn–millet; WF, winter wheat–fallow; WSSF, wheat–sorghum–sorghum–fallow; WW, continuous wheat; WWSF, wheat–wheat–sorghum–fallow.

that long-term NT management decreased BD_{max}, a parameter of soil compactibility, by about 0.20 $Mg\ m^{-3}$ compared with plowed soils. The same study reported that BD_{max} in soils under NT was as low as that in soils under permanent sod (Thomas et al., 1996). Recently, across four soils in the central Great Plains, Blanco-Canqui et al. (2009) reported that near-surface BD_{max} under long-term (between 19 and 43 yr) NT systems was lower than under moldboard plowed and conventionally tilled soils by about 6 to 13%. No-till induced increase in SOC concentration explained 92% of the variability in BD_{max} in Kentucky (Thomas et al., 1996) and 62% in the central Great Plains (Blanco-Canqui et al., 2009), showing that soil's susceptibility to compaction decreased as the NT induced SOC concentration increased. The BD_{max} may be sensitive to small changes in SOC concentration (Davidson et al., 1967).

Published studies on BD_{max} using the Proctor test in agricultural soils have mostly compared differences between plow till and NT practices (Thomas et al., 1996; Blanco-Canqui et al., 2009) and not much those among cropping systems within the same tillage system. On a loam in Oklahoma, moldboard plow continuous cotton (*Gossypium hirsutum* L.) had higher BD_{max} and lower soil organic matter concentration than soils under lespedeza (*Lespedeza striata*) disked once annually (Davidson et al., 1967). Some studies have compared BD_{max} in cultivated against that in noncultivated soils. Across various soils in Argentina, Quiroga et al. (1999) observed that disked and moldboard plowed soils had greater BD_{max} (1.57 $Mg\ m^{-3}$) than noncultivated soils under native vegetation (1.31 $Mg\ m^{-3}$). In the same region, Diaz-Zorita and Grosso (2000) found that BD_{max} decreased from cultivated to noncultivated regardless of differences in soil textural class.

Because of increased concerns over compaction in NT soils, it is imperative to assess how continuous cropping systems can influence risks of soil compaction across a range of soils and NT management systems. To date, no study has documented the possible differences in soil compaction risks among long-term NT cropping systems on regional scales. Characterization of BD_{max} under cropping systems with different levels of biomass C input is needed for a better understanding of effects and causes of soil compaction. Increased SOC in continuous cropping systems may or may not influence soil structural and hydraulic properties (Benjamin et al., 2008), and its impacts on BD_{max} have not been widely researched.

The objectives of this study were to determine differences in BD_{max}, CWC, and ρ_b and the influence of SOC concentration on these compaction parameters for various cropping systems managed under NT in soils in the central Great Plains. Our study hypotheses were that: (i) cropping systems differ in their susceptibility to compaction and (ii) changes in SOC concentration due to differential biomass C input by different cropping systems are responsible for changes in BD_{max}, CWC, and ρ_b. This study differs from previous studies in that it compares differences in soil compactibility among long-term cropping systems within the same tillage system (NT). This study also differs from other studies because it compares the relative differences in BD_{max} against those of ρ_b.

MATERIALS AND METHODS

Description of the Study Soils

This study was conducted across three soils under long-term (>11 yr) cropping systems managed under NT in the central Great Plains. The cropping systems represented common dryland practices in the region. The experiments were at Hays (38°30′ N, 99°11′24″ W) and Tribune (38°16′48″ N, 101°27′36″ W), KS; and Akron (40°8′60″ N, 103°9′ W), CO. These experiments have been in place for 33 yr at Hays, 11 yr at Tribune, and 19 yr at Akron. The soils were Crete silty clay loam (fine, smectitic, mesic Pachic Argiustolls) in Hays; Richfield silt loam (fine, smectitic, mesic Aridic Argiustoll) in Tribune; and Weld loam (fine, smectitic, mesic Aridic Argiustoll) in Akron. The soils at Tribune and Akron are deep and well drained, while the soil at Hays is also deep but moderately slowly permeable. The soil slope at the three sites is <1%. Average annual precipitation is 580 mm in Hays, 440 mm in Tribune, and 421 mm in Akron.

At Hays, there were five cropping systems (SF, SS, WSF, WF, and WW) arranged in a split-plot RCB design with three replicates under reduced till and NT. Cropping systems were the main plots and the tillage systems were the subplots. Each phase of the rotations was present each year. Main plots were 24.4 by 24.4 m in size and subplots were 12.2 by 24.4 m in size. Row spacing was 0.19 m for wheat and 0.76 m for sorghum. Only the five cropping systems under NT were used in this study. Additional details of management are provided by Thompson (2001). At Tribune, there were three cropping systems [wheat–sorghum–sorghum–fallow (WSSF), wheat–wheat–sorghum–fallow (WWSF), and WW] arranged in a RCB design with four replicates managed under NT. Each phase of the rotations was present each year. The wheat phase of the rotation was used for this study. The size of the plots was 12 by 36 m. Row spacing was 0.19 m for wheat and 0.76 m for sorghum.

At Akron, four crop rotations [WF, WCF, WCM, and GRASS) under NT were selected within a larger cropping system experiment. This experiment is laid out in a randomized complete block design (RCBD) with three replicates. Further details of all the cropping systems as well as plot management are reported by Anderson et al. (1999) and Benjamin et al. (2008). Each phase of the rotation was present each year. The phases under wheat were used for this study. The plots under GRASS were under perennial grass including smooth brome (*Bromus inermis* L.) and wheat grass [*Agropyrons trichophorum* (Link) Richt.]. Wheat and millet were planted in 0.19 m rows while corn was planted in 0.76 m rows.

Soil Sampling and Analysis

Approximately 3 kg of bulk soil was collected from each treatment plot at each site for the 0- to 5-cm and 5- to 15-cm depths in summer 2009 for the determination of BD_{max}, CWC, particle-size fractions, and SOC concentration. The samples were air dried at about 20°C for 72 h, gently crushed, and passed through 2-mm sieves for the determination of BD_{max} and particle-size fractions. The BD_{max} and CWC were determined by the Proctor test (American Society for Testing and Materials, 2007). This test consisted of mixing the soil passed through the 2-mm sieves with different amounts of water between air-dry and near saturation and applying a standardized compactive force with the Proctor hammer. The soil sample was thoroughly mixed with water and compacted in three layers in a 0.10-m diam. and 0.12 m high standard Proctor mold. Twenty-five blows per soil layer were applied using a 2.5-kg Proctor drop hammer falling from a 0.30-m height. The compacted soil in the Proctor mold was carefully trimmed and weighed, and 50 g of the compacted soil was oven dried at 105°C for 24 h.

The gravimetric water content of the subsample was extrapolated to that of the compacted soil, and the Proctor bulk density was computed in Mg m^{-3} by dividing the oven-dry mass of the compacted soil by the volume of the Proctor mold. The computed bulk densities were plotted against the gravimetric water content to obtain the Proctor compaction curve. A fifth-order polynomial curve was fitted to the data points to determine both the BD_{max} and the corresponding CWC for each soil sample. The highest point of the polynomial curve was selected as the BD_{max}.

At the time of soil sampling for the Proctor test, intact 5- by 5-cm soil cores were collected from the 0- to 5-cm depth and from the center of 5- to 15-cm depth interval for the determination of ρ_b. The ρ_b was determined by the core method (Grossman and Reinsch, 2002). The sand, silt, and clay content were determined by the hydrometer method using samples passed through 2-mm sieves (Gee and Or, 2002). The particle-size fractions were determined only for the 0- to 5-cm soil depth. The SOC concentration in each sample was determined on air-dry and ground samples passed through 0.25-mm sieves by the dry combustion method (Nelson and Sommers, 1996). The BD_{max}, CWC, and SOC concentration were determined for the 0- to 5-cm and 5- to 15-cm soil depths. The bulk soil samples and soil cores were collected from the nontrafficked rows at each site.

One-way ANOVA model using the PROC GLM in SAS was used to test whether differences in BD_{max}, CWC, sand, silt, and clay content, and SOC concentration were significant. To test differences in Proctor bulk density below BD_{max}, data points for each treatment and replicate were determined from the polynomial curves at selected levels of soil water content. The PROC CORR in SAS was used to establish any relationships among BD_{max}, CWC, particle-size fractions, and SOC concentration. Statistical differences were reported at the 0.05 probability level unless otherwise indicated. The statistical analysis was conducted using SAS statistical software (SAS Institute, 2009).

RESULTS AND DISCUSSION

Maximum Bulk Density and Critical Water Content

The Proctor bulk density vs. soil water content curves for the 0- to 5-cm and 5- to 15-cm depth for the three soils are depicted in Fig. 1A through 1F. Mean BD_{max} for the two depth intervals for each soil is shown in Fig. 2A-2C. The Proctor bulk density curves show that bulk density among the cropping systems differed at soil water contents below the CWC level in the 0- to 5-cm soil depth. Differences were larger for the silty clay loam (Fig. 1A) and loam (Fig. 1C) than for the silt loam (Fig. 1B). On the silty clay loam, mean Proctor bulk density below the CWC in SF and WF was 5 to 15% greater than in WW and SS, while on the loam, it was about 8% greater in WF and WCF than in WCM and GRASS. On the silt loam, WSSF had greater bulk density than WW by 0.1 Mg m^{-3} below 0.10 kg kg^{-1}, but there were no differences at greater water contents (Fig. 1B). For the 5- to 15-cm soil depth, differences in Proctor bulk density were not significant (Fig. 1D-1F).

The BD_{max} was lower in continuous cropping systems than in systems which included fallow (Fig. 2A-2C). On the silty clay loam, mean BD_{max} in SF and WF (1.57 Mg m^{-3}) was greater than in WW and SS (1.47 Mg m^{-3}) by 0.1 Mg m^{-3} (Fig. 2A). On the loam, mean BD_{max} in WF was greater than in WCM by 0.24 Mg m^{-3} and GRASS by 0.11 Mg m^{-3} (Fig. 2C). The BD_{max} in WF did not differ from that in WCF in the loam. Cropping systems did not influence BD_{max} in the silt loam (Fig. 2B). The BD_{max} did not differ in the 5- to 15-cm soil depth.

These results show that long-term continuous cropping systems had a significant impact on reducing near-surface maximum compaction (BD_{max}). Results also show that the magnitude of changes in near-surface BD_{max} among cropping systems depended on soil type and duration of the experiment. The BD_{max} in intensively cropped systems was lower than in crop-fallow systems in the silty clay loam and loam but not in the silt loam. In general, data supported our first hypothesis stating that soil's susceptibility to the relative compaction differs with cropping systems.

The small or no changes in Proctor bulk density in the silt loam but larger differences in the silty clay loam and loam might be due to the following reasons. First, the experiment in the silt loam at Tribune (11 yr) has been in place for shorter time period than the experiments at Hays (33 yr) and at Akron (19 yr). Since changes in soil properties in this climate are often detected after long periods of experimentation, we hypothesize that significant differences in BD_{max} and SOC concentration in the silt loam may surface in the longer term. Second, cropping systems differed among the three soils. The experiment in the silty clay loam and loam included more contrasting cropping systems (crop-fallow vs. continuous cropping systems) than that in the silt loam with only three systems (WSSF, WWSF, and WW). Fallow periods occurred every 2 yr for the WF and SF in the silty clay loam and WF in the loam, whereas in the silt loam, they occurred every 4 yr. Thus, the less contrasting differences in cropping systems in the silt loam than in other soils probably reduced differences in soil compactibility due to smaller differences in surface residue cover, biomass C input, and soil properties.

Similar to BD_{max}, cropping systems also altered CWC in the silty clay loam and loam but not in the silt loam (Fig. 3A-3C). The CWC in the silty clay loam (Fig. 3A) differed only in the 0- to 5-cm depth, but, in the loam, it differed at both depth intervals (Fig. 3C). On the silty clay loam, the CWC in WW and SS was greater than in WF and WSF by 0.02 kg kg^{-1} and SF by 0.04 kg kg^{-1} (Fig. 3A). On the loam, the CWC in WCM was greater than in GRASS by 0.015 kg kg^{-1} and WF and WCF by 0.05 kg kg^{-1} in the 0- to 5-cm depth. At the same depth, the CWC in GRASS was greater than in WF and WCF by about 0.04 kg kg^{-1}. For the 5- to 15-cm depth, CWC in WCM and GRASS was greater than in WF and WCF by 0.025 kg kg^{-1}. The BD_{max} was very strongly and negatively correlated ($r > -0.8$; $P < 0.001$) with CWC in all soils (Fig. 4A-4D). The BD_{max} decreased with an increase in CWC. The CWC explained 64% of the variability in BD_{max} in the silty clay loam (Fig. 4A), 74% in the silt loam (Fig. 4B), and 75% in the loam (Fig. 4C). Across all soils, CWC explained 88% of the variations in BD_{max} (Fig. 4D).

Results of this study showed that the relative maximum soil compaction in continuously cropped systems occurred at greater soil water content than in crop-fallow systems (Fig. 3A-3C). For example, mean CWC increased by about 0.05 kg kg^{-1} from SF to WW and SS in the silty clay loam (Fig. 3A) and from WF to WCM in the loam (Fig. 3C). Thus, results suggest that soils in continuous cropping systems may be trafficked at greater soil water contents than those in crop-fallow systems without causing excessive compaction. It is also clear from the results that differences in near-surface Proctor

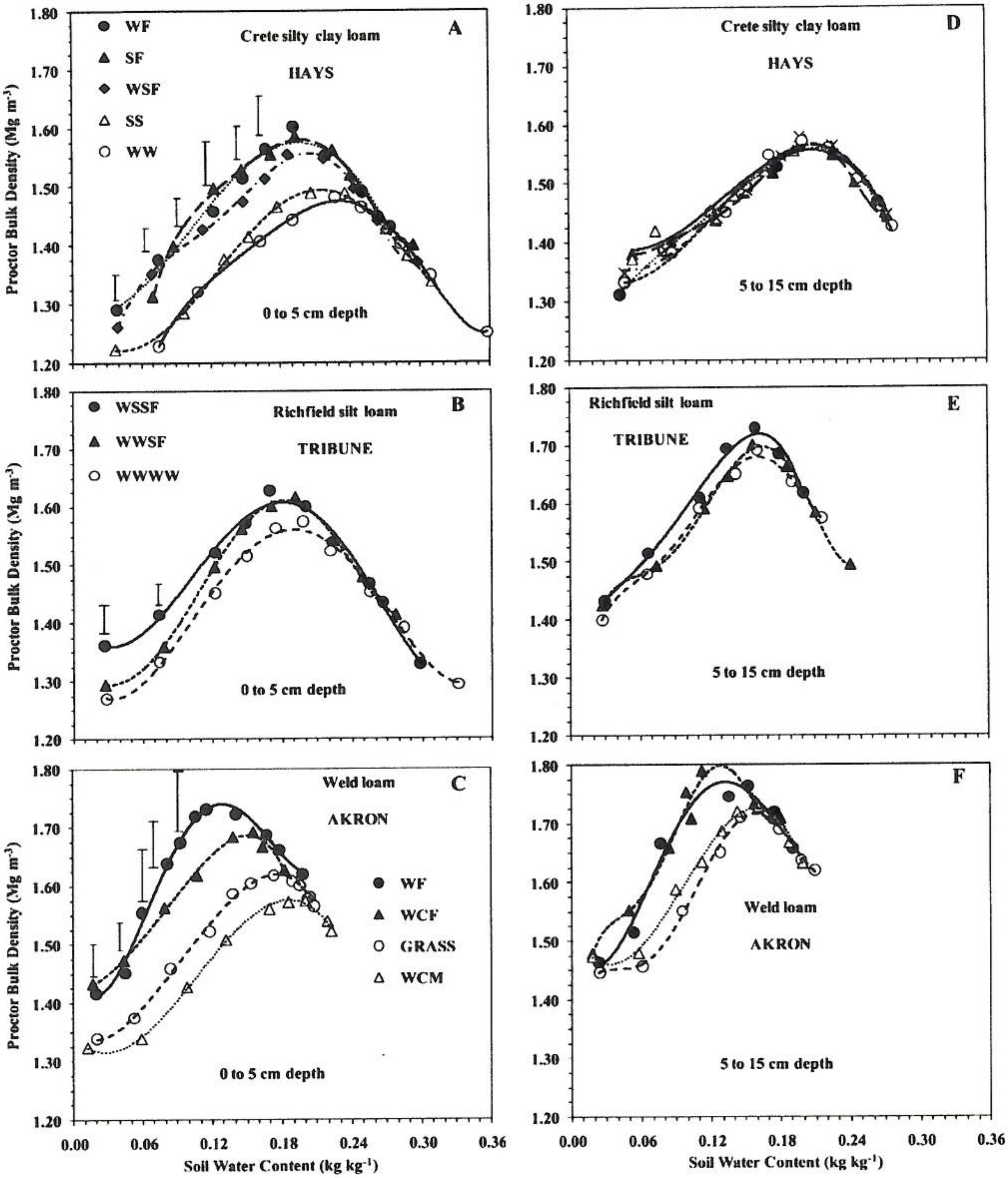

Fig. 1. Relationship of Proctor bulk density with soil water content for the 0- to 5-cm depth (A–C) and 5- to 15-cm depth (D–F) for three soils under A and D) wheat-fallow (WF), sorghum–fallow (SF), wheat–sorghum–fallow (WSF), continuous sorghum (SS), and continuous wheat (WW), (B and E) wheat–sorghum–sorghum–fallow (WSSF), wheat–wheat–sorghum–fallow (WWSF), and WW, and C and F) wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–millet (WCM), and perennial grass (GRASS). Error bars represent the LSD values where differences among the cropping systems at selected levels of soil water content were significant.

bulk density differed only below the CWC, which indicate that continuous cropping systems can alleviate some of the risks of excessive compaction at low rather than at high soil water contents. Above the CWC, all soils were equally compacted regardless of differences in cropping systems.

Field Bulk Density, Particle-Size Fractions, and Soil Organic Carbon

Cropping systems altered ρ_b only in the silty clay loam and loam (Fig. 5A-5C). Differences in ρ_b were similar to those in BD_{max} and CWC. On the silty clay loam, mean ρ_b averaged

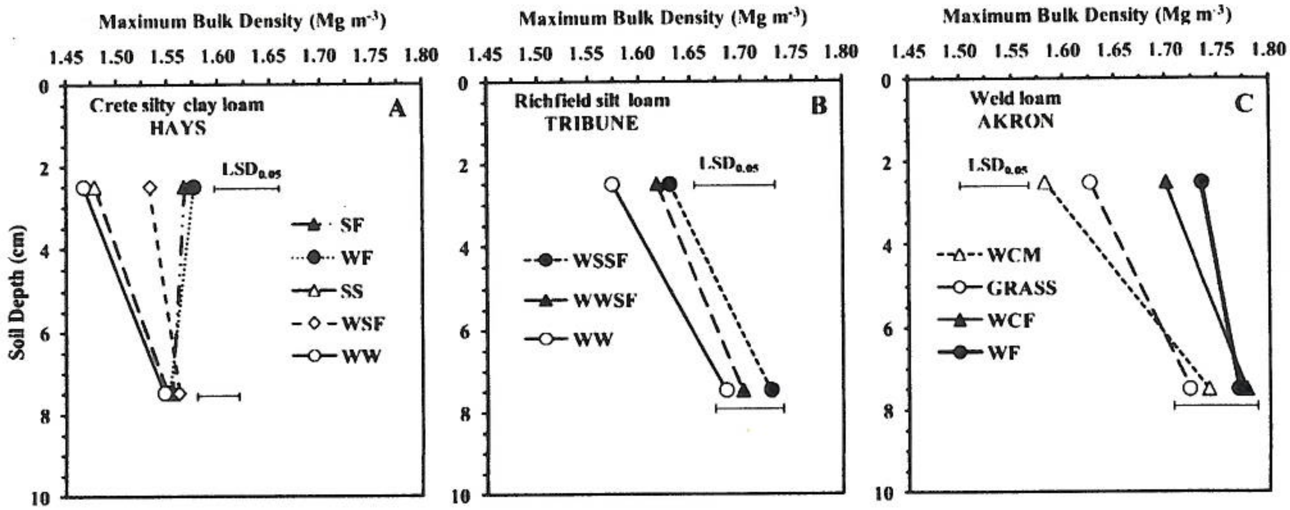

Fig. 2. Maximum bulk density using Proctor test by depth for three soils under (A) wheat–fallow (WF), sorghum–fallow (SF), wheat–sorghum–fallow (WSF), continuous sorghum (SS), and continuous wheat (WW); (B) wheat–sorghum–sorghum–fallow (WSSF), wheat–wheat–sorghum–fallow (WWSF), and WW; and (C) wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–millet (WCM), and perennial grass (GRASS).

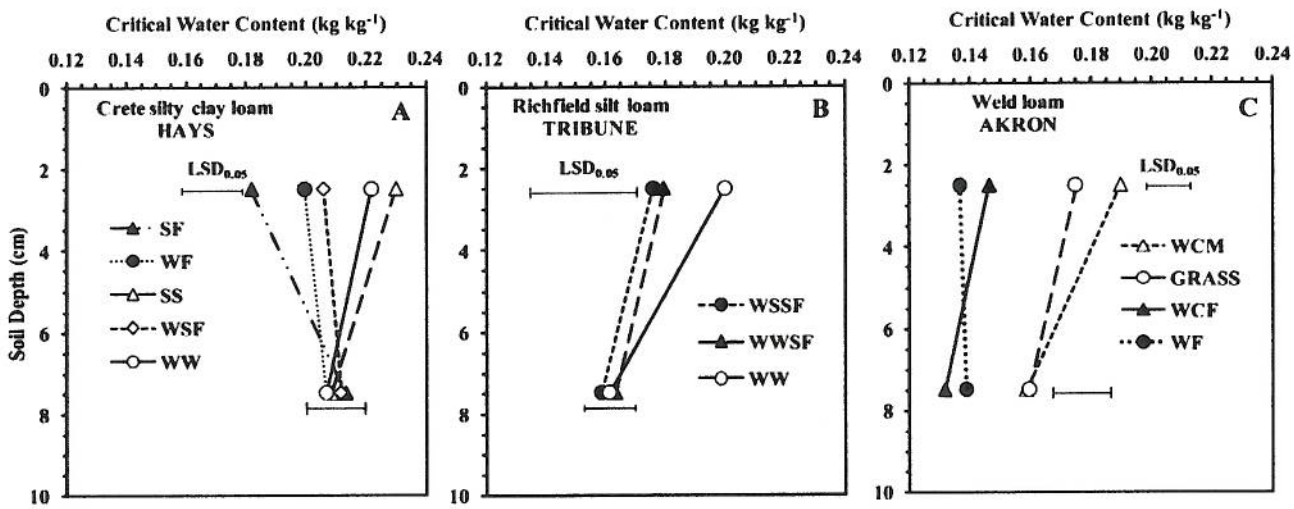

Fig. 3. Critical water content using Proctor test by depth for three soils under (A) wheat–fallow (WF), sorghum–fallow (SF), wheat–sorghum–fallow (WSF), continuous sorghum (SS), and continuous wheat (WW); (B) wheat–sorghum–sorghum–fallow (WSSF), wheat–wheat–sorghum–fallow (WWSF), and WW; and (C) wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–millet (WCM), and perennial grass (GRASS).

across SF, WF, WSF, and SS (1.41 Mg m^{-3}) was greater than in WW (1.16 Mg m^{-3}) by about 22% in the 0- to 5-cm depth. For the 5- to 15-cm depth, there were no statistical differences in ρ_b. On the loam soil, mean ρ_b averaged across WF and WCF (1.38 Mg m^{-3}) was greater than that averaged across WCM and GRASS (1.21 Mg m^{-3}) by 14% in the 0- to 5-cm depth. There were no differences in sand, silt, and clay content among the cropping systems at any of the soils (data not shown). Sand content averaged across all cropping systems was 166, 140, 250 g kg^{-1} at Hays, Tribune, and Akron locations, respectively, while clay content was 370, 400, and 320 g kg^{-1} at Hays, Tribune, and Akron locations, respectively.

The SOC concentration differed among cropping systems except in the silt loam (Fig. 6A-6C). On the silty clay loam, SOC concentration under WW was 1.5 times greater than the average across WF, WSF, and SS and 2.0 times greater than in SF in the 0- to 5-cm depth (Fig. 6A). For the 5- to 15-cm depth, SOC concentration in WW was greater than in WF and SF by 1.4 times, while that in SS was greater than in SF by 1.5 times. On the loam, SOC concentration under GRASS was greater by 1.4 times while that under WCM was greater by two times than the average across WF and WC in the 0- to 5-cm depth (Fig. 6C). There were no differences in SOC concentration in the 5- to 15-cm depth in the silt loam and loam.

Relationships between Soil Compaction Parameters and Soil Organic Carbon

The reduction in BD_{max} by continuous cropping systems is largely attributed to the near-surface accumulation of SOC. The BD_{max} was highly and negatively correlated (Fig. 7A-7D) with SOC concentration for the 0- to 15-cm depth in all soils, supporting our second hypothesis. The BD_{max} decreased in a linear function with an increase in SOC concentration. The BD_{max} was less strongly correlated with SOC concentration for the silty clay loam than for the silt loam and for the loam. Changes in SOC concentration explained 28% of the variations in BD_{max}

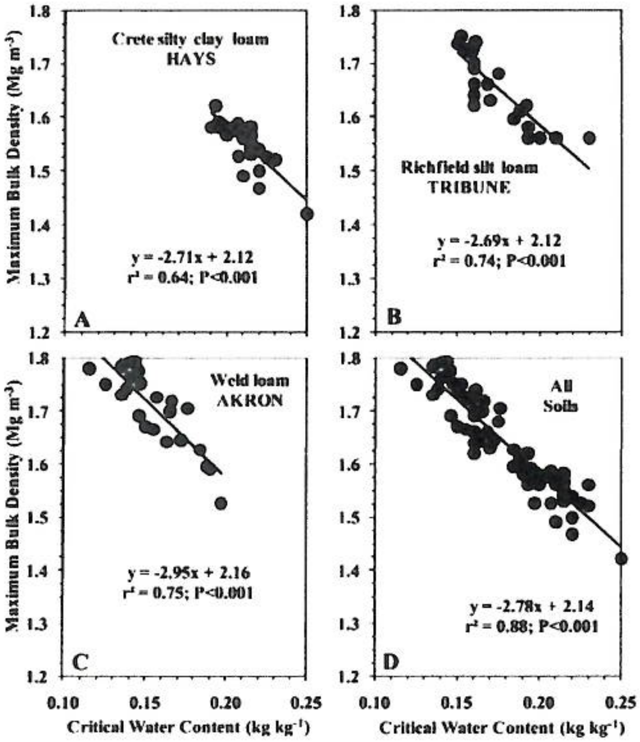

Fig. 4. Relationship between maximum bulk density and critical water content by the Proctor test for three soils (A–C) and across all soils (D) under different cropping systems.

for the silty clay loam (Fig. 7A), 43% for the silt loam (Fig. 7B), and 72% for the loam (Fig. 7C). Across the three soils, changes in SOC concentration explained 71% of the variations in BD_{max} (Fig. 7D). It is important to note that while the BD_{max} and SOC concentration among crop rotations did not statistically differ in the silt loam, BD_{max} significantly decreased with an increase with SOC concentration as a result of lower, although not statistically significant, BD_{max} (Fig. 2B) and greater SOC concentration (Fig. 6B) in WW than in WWSF and WSSF.

The ρ_b was also significantly correlated with SOC concentration (Fig. 8A-8D). Similar to BD_{max}, the ρ_b decreased with an increase in SOC concentration in all soils. Changes in SOC concentration explained 23% of the variations in BD_{max} for the silty clay loam (Fig. 8A), 39% for the silt loam (Fig. 8B), and 66% for the loam (Fig. 8C). Across the three soils, changes in SOC concentration explained 32% of the variations in BD_{max} (Fig. 8D). The relationship between ρ_b and SOC concentration was, however, weaker than that between BD_{max} and SOC concentration. Across all soils, changes in SOC concentration explained 71% of the variability in BD_{max} (Fig. 7D), but they explained only 32% of the variability in ρ_b (Fig. 8D). The BD_{max} and ρ_b were significantly related. Changes in ρ_b explained about 30% of the variability in BD_{max}.

The increase in CWC was also attributed to an increase in SOC concentration with continuous cropping systems as the CWC was strongly correlated with SOC concentration (Fig. 9D). The CWC increased with an increase in SOC concentration (Fig. 9A-9D), but the magnitude of the relationships varied with soil. Changes in SOC concentration explained 16% of the variability in CWC in the silty clay loam (Fig. 9A), 44% in the silt loam (Fig. 9B), and 45% in the loam (Fig. 9C). Across the three soils, SOC concentration accounted for 65% of the variations in CWC (Fig. 9D). The sand, silt, and clay content were not correlated with BD_{max}, CWC, and SOC concentration in any soil (data not shown).

The reduced soil's susceptibility to compaction and compression with increased SOC concentration is attributed to the following mechanisms induced by soil organic matter (Soane, 1990; Aragón et al., 2000; Ball et al., 2000). First, soil organic matter increases the soil's resistance to deformation by improving the elasticity and rebounding capacity of the soil matrix. Soil organic materials are more elastic and looser than mineral particles. Second, soil organic matter lowers the bulk density of the whole soil by the "dilution effect" as it has a lower bulk and particle density than mineral particles. Third, organic compounds of high molecular weight contribute to the bonding of organic and mineral particles at the contact points inside the macro- and microaggregates, improving the resilience against soil consolidation and compaction. Fourth, soil organic matter may alter the electrical charge of organomineral contact points and increase friction between organic and mineral particles, which would reduce consolidation of aggregates.

Results of this study also indicate that the relative maximum compactive force that these soils can resist without being

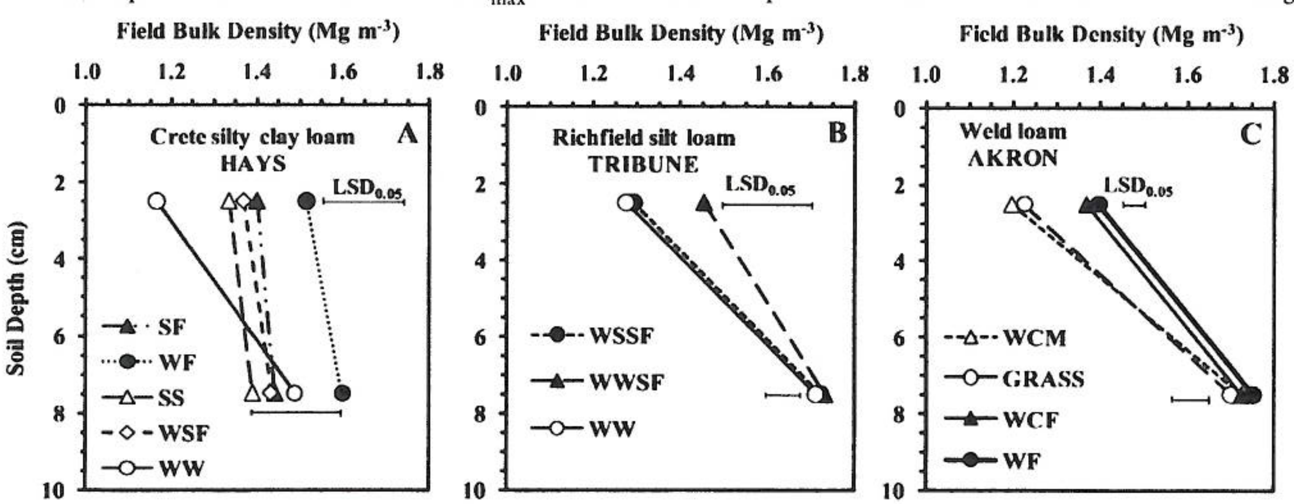

Fig. 5. Field bulk density by depth for three soils under (A) wheat–fallow (WF), sorghum–fallow (SF), wheat–sorghum–fallow (WSF), continuous sorghum (SS), and continuous wheat (WW); (B) wheat–sorghum–sorghum–fallow (WSSF), wheat–wheat–sorghum–fallow (WWSF), and WW; and (C) wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–millet (WCM), and perennial grass (GRASS).

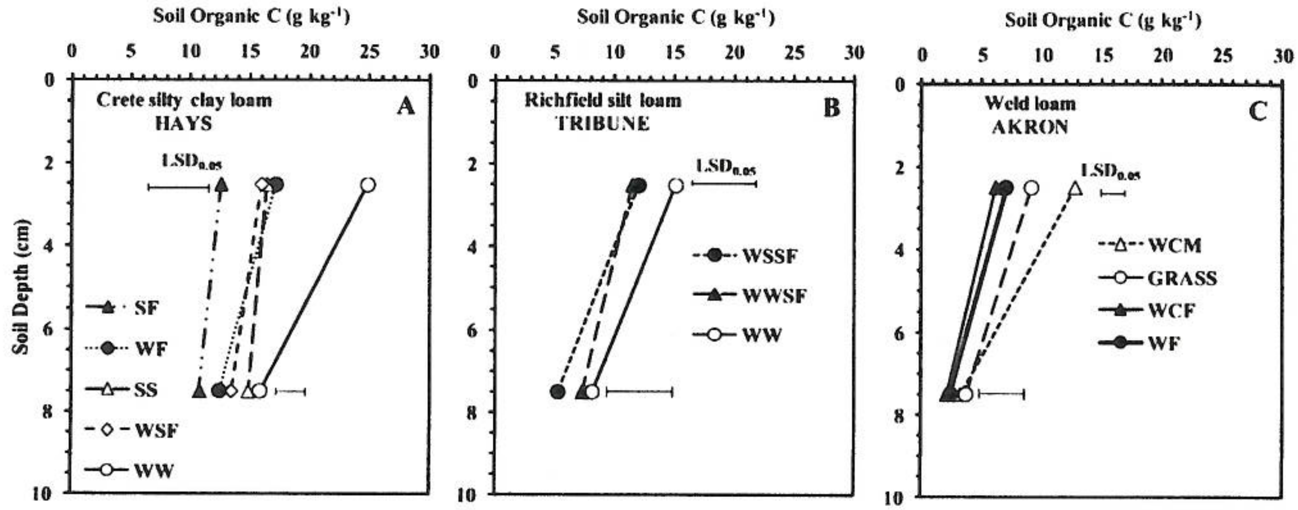

Fig. 6. Soil organic C concentration by depth for three soils under (A) wheat–fallow (WF), sorghum–fallow (SF), wheat–sorghum–fallow (WSF), continuous sorghum (SS), and continuous wheat (WW); (B) wheat–sorghum–sorghum–fallow (WSSF), wheat–wheat–sorghum–fallow (WWSF), and WW; and (C) wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–millet (WCM), and perennial grass (GRASS).

compacted depends on SOC concentration. These results may have large implications because they suggest that near-surface excessive maximum compaction may be somewhat managed by adopting continuous cropping systems which increase SOC concentration. Crop-fallow systems had lower SOC concentration than continuous cropping systems and thus they were more prone to compaction than cropping systems without fallow periods. The confinement of the beneficial impacts of increased SOC concentration on reducing soil compaction to the upper 0- to 5-cm soil depth is attributed to the stratification of SOC concentration in these NT soils.

Soil water content, particle-size distribution, and SOC concentration are among the soil factors influencing soil compactibility (Aragón et al., 2000; Ball et al., 2000; Díaz-Zorita and Grosso, 2000). Among these factors, SOC concentration is probably the only factor that can be altered by cropping systems as soil water content changes dynamically with precipitation. Improved management strategies that increase SOC concentration at lower depths and reduce SOC stratification are needed. Growing deep-rooted plant species such as forage grass (Peterson and Westfall, 2004; Benjamin et al., 2007) and manure application (Blanco-Canqui et al., 2005) may be alternatives to

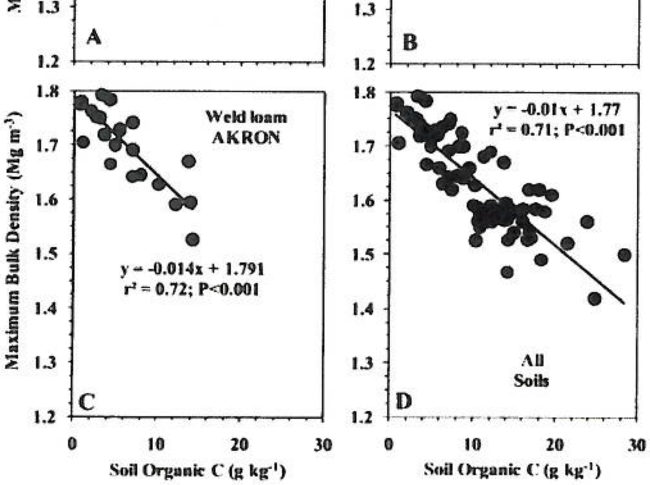

Fig. 7. Relationship between maximum bulk density and soil organic C concentration for three soils (A–C) and across all soils (D) under different cropping systems.

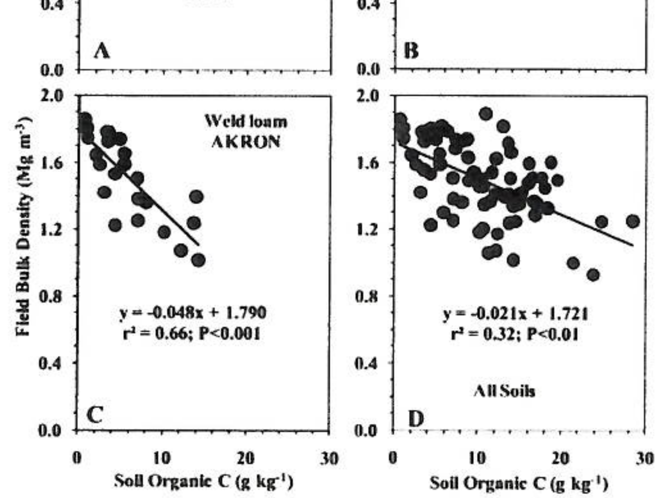

Fig. 8. Relationship between field bulk density and soil organic C concentration for three soils (A–C) and across all soils (D) under different cropping systems.

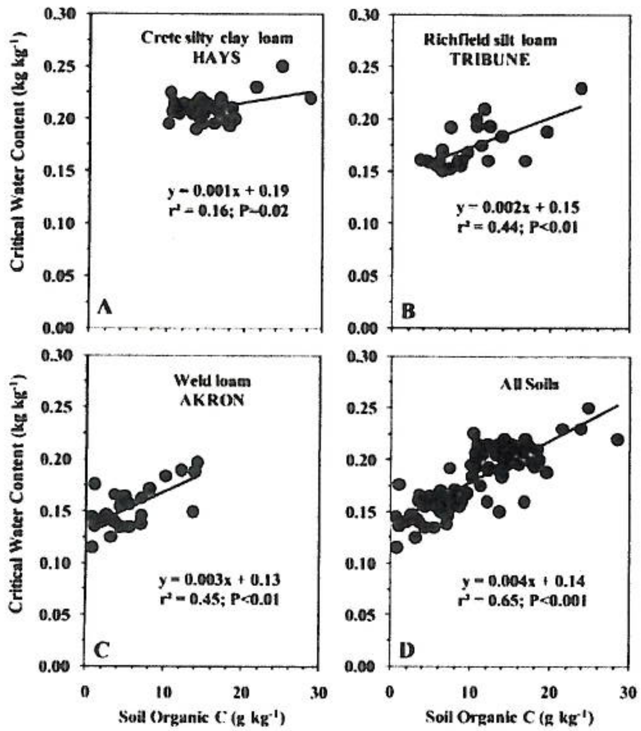

Fig. 9. Relationship between critical water content at the maximum bulk density by the Proctor test and soil organic C concentration for three soils (A–C) and across all soils (D) under different cropping systems.

increase SOC concentration with depth in cultivated soils and offset some of the risks of soil compaction in deeper soil depths. Data for the loam from Akron indicate that growing perennial in cultivated soils increased SOC concentration and reduced risks of soil compaction.

It is important to indicate that the results from this study should be interpreted cautiously. The Proctor test provides information on the relative differences in soil compactibility because it uses homogenized soil samples, which do not fully reflect in situ field conditions. The Proctor bulk density is determined using large and disturbed soil samples, whereas field ρ_b is determined on small and undisturbed soil cores. These differences in size and disturbance in soil samples may partly explain the relatively weak relationship between BD_{max} and ρ_b ($r^2 = 0.30$; $P < 0.001$) in our study.

Characterization of relative bulk density using the Proctor test provides nevertheless the following additional information over ρ_b determinations. First, the Proctor test permits the identification of BD_{max} of a soil under a systematic, uniform, and repeatable application of compactive forces, simulating the pressure exerted by field equipment. Second, it permits the determination of the "critical water content" (CWC) for maximum soil compaction so that the soil can be trafficked below this CWC level without causing excessive compaction. Third, it allows the breakdown of soil compaction risks at various soil water contents, simulating the effects of field soil water dynamics on soil compaction. For example, in this study, the Proctor test allowed the determination that continuous cropping systems had greater effect on reducing bulk density at low rather than at high soil water contents. As stated earlier, both BD_{max} and ρ_b decreased linearly with an increase in SOC concentration, but BD_{max} was more strongly correlated (Fig. 7D) with SOC concentration than with ρ_b (Fig. 8D).

CONCLUSIONS

This regional study across three contrasting soils in the central Great Plains shows that long-term continuous cropping systems may alleviate some of the risk of excessive near-surface soil compaction over crop-fallow systems in no-till systems. The near-surface maximum bulk density, a parameter of soil compactibility, under continuous cropping systems was significantly lower than under crop-fallow systems in two of the three soils studied. These results indicate that reduction or elimination of fallow periods may reduce some of the risks of soil compaction near the soil surface layers. Continuous cropping systems also increased the soil water content at which a soil can be trafficked without significantly inducing excessive compaction. For the same compactive force, soils under crop-fallow systems become compacted at lower water content than those under continuous cropping systems. Continuous cropping systems increased SOC concentration over crop-fallow systems, and the maximum bulk density decreased and critical water content increased with an increase in SOC concentration. Thus, continuous cropping system induced increase in SOC concentration was primarily responsible for the reduced relative compactibility in these no-till soils. Data suggest that increasing SOC concentration through appropriate management practices such as continuous cropping systems may be potential means for managing compaction within the surface layers.

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